Appendix 2

Subjective Assessments of Audio Quality of DAR Systems

I. Introduction

This document describes the procedures and results of subjective tests conducted at the Communications Research Centre (CRC), Ottawa, Ontario, Canada, performed to assess the audio quality of digital audio radio (DAR) systems submitted to the Electronic Industries Association's Digital Audio Radio Subcommittee.

A total of nine DAR systems were submitted for testing and are labeled in these results as *a* to *i*. Subjective audio quality was assessed in the absence of any transmission error, thus evaluating the quality of the audio source coding component of each system. One of the nine systems was tested with two different comparison references because the sampling rate for that system was lower than for the other 8 systems, and this report refers to 10 systems noted as *a* to *j*.

II. Subjective Assessment Procedures

A panel of three expert listeners selected final test materials from the initial pool of program segments received from the evaluation subcommittees. This panel selected nine materials, two of which were stressful to each system under test. These are listed in Table 1.

A total of 21 listeners went through the test process for two days each, to complete the 90 rating trials (10 systems x 9 materials). The equipment, listening environment and procedures were the standard ones used in subjective tests at the CRC as described in ITU-R Rec. BS.1116 [1] Statistical evaluations assessed each individual's listening expertise by way of a *t*-test, which showed that no listener who took part in the experiment scored below 2.00. Therefore, they all showed that they were able to discriminate correctly between hidden reference and system versions across all the trials in the experiment.

The actual scale used by the subjects is shown in Figure 1. It is a 5 grade rating scale (1.0 to 5.0) where listeners were instructed to use a single decimal point. In effect, this is a 41 point scale. The subjects were instructed to treat this as a continuous scale but, to facilitate the subjects' orientation, category labels were associated with the scale. Thus, 1.0 to 1.9 is a "very annoying" range; 2.0 to 2.9 is "annoying"; 3.0 to 3.9 is "slightly annoying"; 4.0 to 4.9 is "perceptible but not annoying". Finally, 5.0 is "imperceptible".

The listener's task on a trial is to compare each of two alternative versions of an audio material labeled "B" and "C" with a known Reference version, labeled "A", of the same material. The subject knows that one of the alternatives ("B" or "C") is a "hidden reference", identical to the Reference, and that the other alternative is one that has been processed through a DAR system. The subject does not know which is which, but must decide this through listening. He or she then assigns a grade to both "B" and "C" alternatives, as compared to the known Reference "A", using the 1.0 to 5.0 scale. A is that the alternative the subject has decided is the "hidden reference" must be graded 5.0. And so, *at least one* of the two grades on each trial must be a 5.0

Thus two totally interdependent scores from the listener are recorded on each trial. This deliberate interdependence is handled by subtracting the score given to the true hidden reference from the score given the true processed version (i.e., DSB System minus reference). so that in a graphical plot of outcomes, the data will fall in the same geometric quadrant as they would if the actual 1.0 to 5.0 scores used by the subjects were plotted. Thus the scores are transformed so that the 1.0 to 5.0 range of the original scale becomes, instead, -4.0 to 0.0 in the analysis and presentation of results. These difference grades or "diffgrades" represent the relative differences between the grades given to the hidden reference and the ones given to the DSB system under test.

III. Test Results

For visual clarity, the average quality diffgrades obtained in the experiment are divided between Figures 2(a) and 2(b) rather than being shown within a single graph. Six of them appear in the first figure, four in the second. In addition to the average score among the listeners for each of the audio materials, the overall average diffgrade (the average across all audio materials for each system) is plotted in the "System Averages" column at the right-hand side of these Figures.

Table 2 shows the overall average diffgrade for each audio material and for each system as well as the overall (average) diffgrade for each system in the right-hand column. This table shows all the numbers that are plotted in Figure 2(a) and 2(b). In Table 2, the average diffgrades across all listeners for each audio material occupy a separate row for each DSB system. The average diffgrades are entered to two decimal figures. Systems are arranged by row in alphabetical order using the letters attributed to the ten systems tested -- part of the "double blind" procedures followed throughout the tests..

IV. Overall System Results

The statistical method used to evaluate the present results is the Analysis of Variance (ANOVA) which has been officially recommended in ITU-R Rec. BS.1116 [1]. The experimental design used for these tests permitted the rigorous application of this analytic method. The first item for discussion is the overall average diffgrade for systems. The ANOVA showed that the overall experimental differences among systems in the tests have a very fine resolution of 0.17 of a grade in the transformed diffgrade scale.

For completeness, however, if a reader is interested in evaluating overall differences among audio materials independent of systems (as shown in the averages in the bottom row of Table 2), the critical value provided by the ANOVA is 0.23. This applies to the "without *i* and *j*" averages. Thus, any two of the 9 audio material averages ("without *i* and *j*") across systems must differ by at least 0.23 before they can be considered significantly different on statistical grounds.

The "two" systems (*i* and *j*) rate differences in the references against which subjects compared them. System are actually the same coding system. But they were treated differently in the experiment because of sampling rate differences in the references against which subjects compared them;. System *i* was always compared with 32 kHz sampling rate references, while for system *j*, the references were always sampled at 48 kHz. The ANOVA showed that the overall difference between *i* and *j* were 0.01, well below the 0.17 needed for a conclusion of significant difference.

V. Interaction of Systems with Audio Materials

The ANOVA reveals that the resolution for the interaction of audio materials and systems in this experiment is 0.45 of a grade. This too is a very fine degree of resolution for interactions of this type. When comparing diffgrades between any two systems for any given audio material in Figure 2(a) and 2(b), Table 4 and Figure 3, a numerical difference of 0.45 or greater is required before it can be concluded that those two diffgrades are statistically different from each other rather than being due to chance ($p<0.05$).

VI. Summary

Table 3 shows system identifications in the first column, summarizing the major outcomes using the three criteria developed and used by the ITU-R to evaluate the relative merits of audio coding systems.

First, the overall average diffgrade is shown for each system. This is presented in the second column of the table. Secondly, to summarize the interaction of audio materials by systems and to indicate the size of the variability of each system, the number of times each system fell below a diffgrade of -1.0 for the 9 materials is presented in the third column of the table. To take statistical error into account, the number of times that any system's lower error bar fell "below -1.0" for any material in Figure 3 provided the count shown in this third column. Finally, another ITU-R criterion related to the variability or consistency of each system is shown in the fourth column. This is the number of times that a system could be considered "transparent" for an audio item. The number of times that any system's upper error bar fell above 0.0 in the charts of Figure 3 provided the count shown in this fourth column. Table 3 also shows the systems associated with their letter codes.

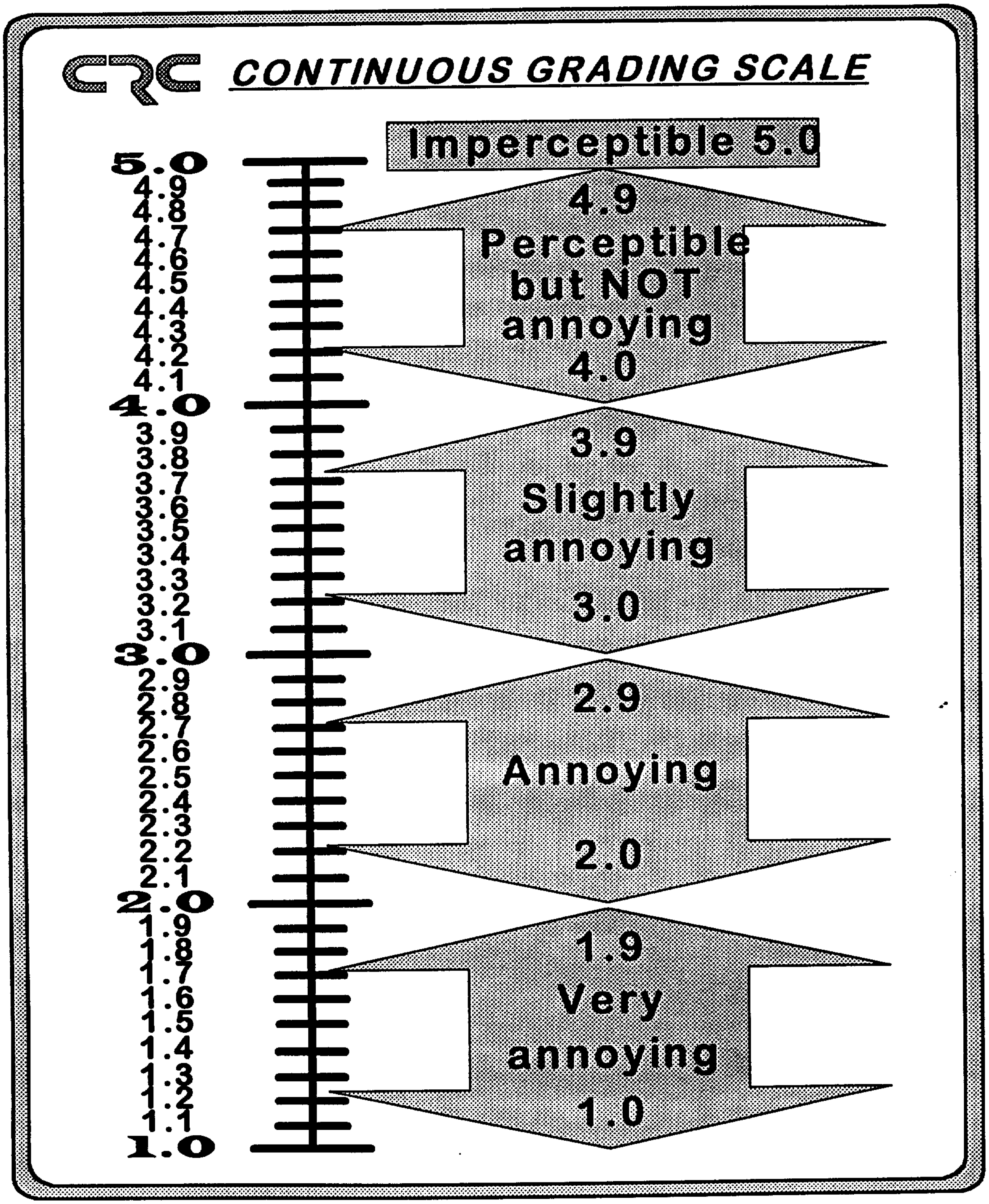


Figure 1 ITU-R continuous 5-grade impairment scale

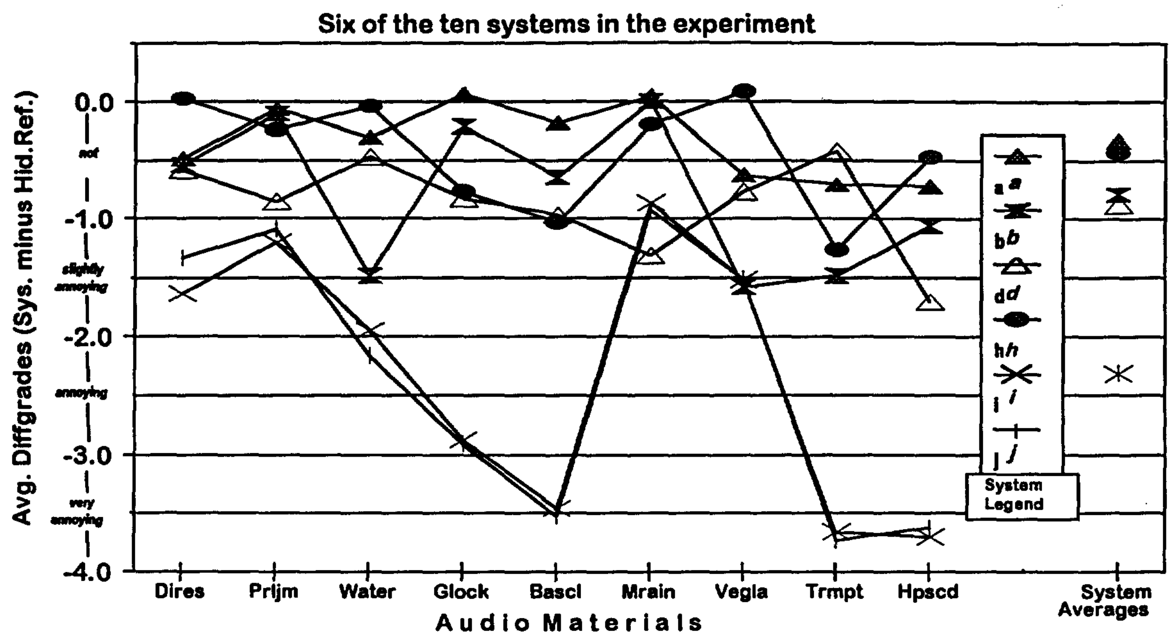


Figure 2(a) Quality test results - systems a,b,d,h,i &j

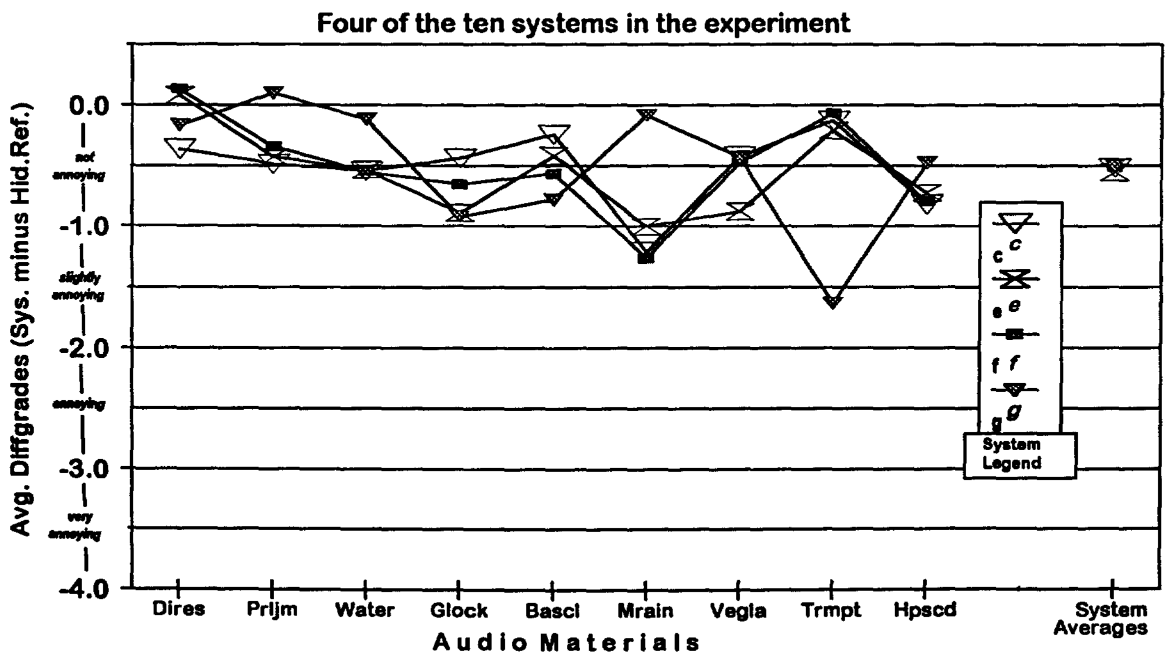
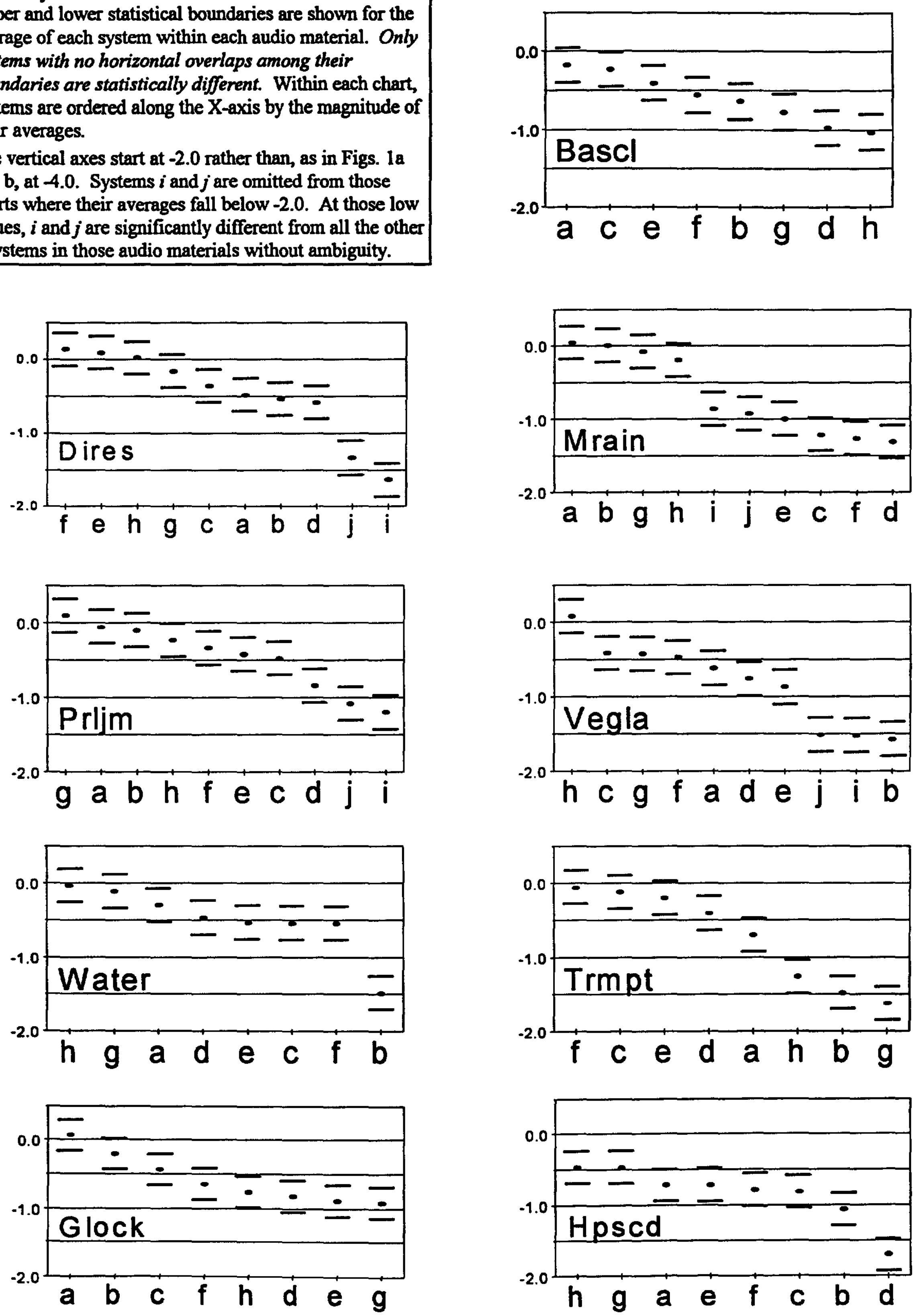


Fig. 2(b) Quality test results - systems *c*, *e*, *f*, and *g*

Fig. 3 System Differences Within Audio Materials
Upper and lower statistical boundaries are shown for the average of each system within each audio material. ***Only systems with no horizontal overlaps among their boundaries are statistically different.*** Within each chart, systems are ordered along the X-axis by the magnitude of their averages.
The vertical axes start at -2.0 rather than, as in Figs. 1a and b, at -4.0. Systems *i* and *j* are omitted from those charts where their averages fall below -2.0. At those low values, *i* and *j* are significantly different from all the other 8 systems in those audio materials without ambiguity.



Code	Description	Duration	Source
Dires	Dire Straits cut	30 s	Warner Bros. CD 7599-25264-2 (track 6)
Prljm	Pearl Jam cut	30 s	Sony/Epic CD ZK53136 (track 3) with processing[1]
Water	Sounds of water	30 s	Roland Dimensional Space Processor Demo. CD
Glock	Glockenspiel	16 s	EBU SQAM CD (track 35/Index 1)
Bascl	Bass Clarinet arpeggio	30 s	EBU SQAM CD (track 17/Index 1) with processing[1]
Mrain	Music and rain	11 s	AT&T mix
Vegla	Susan Vega with glass	11 s	AT&T mix
Trmpt	Muted trumpet	9 s	Original DAT recording, University of Miami
Hpscd	Harpsichord arpeggio	12 s	EBU SQAM CD (track 40/Index 1)

[1] Processing chain used: Aphex Compellor Model 300 (set for leveling only)
Dolby Spectral Processor Model 740
Aphex Dominator II Model 720

Table 1 List of audio test materials used in the quality tests

The data for a single system are shown throughout each row.

System	Dires	Prljm	Water	Glock	Bascl	Mrain	Vegla	Trmpt	Hpscd		Overall Averages
a	-0.49	-0.06	-0.30	0.07	-0.18	0.04	-0.62	-0.70	-0.72	*a*	-0.33
b	-0.54	-0.10	-1.49	-0.21	-0.64	0.00	-1.58	-1.49	-1.07	*b*	-0.79
c	-0.36	-0.49	-0.54	-0.44	-0.24	-1.21	-0.42	-0.12	-0.82	*c*	-0.52
d	-0.59	-0.85	-0.47	-0.82	-0.97	-1.31	-0.77	-0.41	-1.70	*d*	-0.88
e	0.09	-0.43	-0.53	-0.89	-0.41	-1.00	-0.88	-0.20	-0.72	*e*	-0.55
f	0.14	-0.34	-0.55	-0.65	-0.57	-1.26	-0.47	-0.06	-0.80	*f*	-0.51
g	-0.16	0.10	-0.11	-0.92	-0.78	-0.08	-0.43	-1.63	-0.48	*g*	-0.50
h	0.02	-0.24	-0.04	-0.77	-1.04	-0.20	0.08	-1.27	-0.47	*h*	-0.43
i	-1.64	-1.20	-1.95	-2.87	-3.46	-0.86	-1.52	-3.66	-3.70	*i*	-2.32
j	-1.34	-1.09	-2.16	-2.91	-3.52	-0.93	-1.51	-3.73	-3.62	*j*	-2.31
Audio Material Averages	-0.49	-0.47	-0.81	-1.04	-1.18	-0.68	-0.81	-1.33	-1.41		-0.91
Averages Without *i* and *j*	-0.24	-0.30	-0.50	-0.58	-0.60	-0.63	-0.64	-0.74	-0.85		-0.56

System *i* received a grade of -1.95 for Water. In view of the statistical error (0.45 of a grade), *i* was omitted from Water in Fig. 2.3 on the next page, along with other instances of *i* and *j* in materials where either of these two systems obtained a diffgrade lower than -2.00. (No systems other than *i* and *j* received any diffgrades below -2.00.)

Table 2: Average Difference Grades for each of the 9 Audio Materials (columns) by each of the 10 Systems

System Designation	Overall Average Diffgrade	Number of transparent materials	Number of materials below -1.0
A - Eureka 147, MUSICAM @ 224 kbps	-0.33	4	0
B - Eureka 147, MUSICAM @ 192 kbps	-0.79	3	4
C - AT&T/Lucent, PAC @ 160 kbps	-0.52	2	1
D - AT&T/Amati, DSB PAC @ 160 kbps	-0.88	5	0
E - AT&T/Amati, LSB PAC @ 160 kbps	-0.55	3	2
F - VOA/JPL, PAC @ 160 kbps	-0.51	2	2
G - USADR FM-2, MUSICAM @ 256 kbps	-0.50	2	4
H - USADR FM-1, MUSICAM @ 256 kbps	-0.43	2	4
I - USADR AM, MUSICAM @ 96 kbps (32 kHz reference)	-2.32	0	9
J - USADR AM, MUSICAM @ 96 kbps (48 kHz reference)	-2.31	0	9

Table 3
Summary of Audio Quality Tests

Appendix 3

Digital Sound Broadcasting Impairment Test Results

Introduction

This document is intended to focus only on the digital impairment tests for all seven systems. Complete laboratory test results for all seven systems are available from EIA.

Up to three audio test segments that originated from the EBU SQAM disc, glockenspiel, soprano, and clarinet were used for transmission impairment tests.

The desired signal receiver input level for the impairment tests was -62 dBm for the systems in the FM band systems and -60 dBm for the L and S band.

Gaussian Noise, Co-Channel, and Multipath and Noise Tests

For the noise test filtered gaussian noise was added to the signal and the noise increased until the threshold of audibility was heard by the laboratory specialists. The Threshold Of Audibility (TOA) is the point where the interference is just perceptible. From the TOA the noise was further increased until the point of failure was heard. Point Of Failure (POF) is the point where the signal completely fails or the interference is very annoying. A remotely controlled 0.25 dB steps attenuator was used to find the TOA and POF. Digital audio tapes were made with the added noise level ranging from below TOA to a level above POF. These recordings were used for further subjective assessment at the Communications Research Centre. Laboratory type average power meters were used to measure signal power.

Table #1 shows the results of the noise tests with the three audio segments. To compensate for the differing digital bandwidths (0.2 MHz to 1.5 MHz), the performance for added noise was calculated using C_o/N_o. The TOA/POF noise spreads varied 4.2 dB from shortest to the longest. The AT&T IBAC system had a 0.8 dB spread and the USADR FM-1 IBOC had a 5 dB spread.

Co-Channel

Each proponent supplied a second system transmitter or a system simulator for the co-channel tests. The co-channel signal was increased in 0.25 dB steps until the TOA and POF were heard by the laboratory specialists. The results of the tests are in desired/undesired (D/U) signal ratios. Digital audio tapes were recorded with the co-channel ranging from just below TOA to above POF for further subjective assessment at the CRC.

Table #2 shows the results of the co-channel tests. The TOA/POF spreads for co-channel were slightly higher than those for noise.

Multipath and Noise Tests

The simulated multipath and noise tests were conducted twelve times, each with a different multipath scenario: urban slow, urban fast, rural fast, and terrain obstructed, using three audio segments for each scenario. The multipath parameters were specified by the channel characterization sub-group. Digital recordings were made for further subjective assessment at the CRC.

Table #3 shows the laboratory test results with three audio test materials and the four multipath scenarios. If impairments were heard without noise added, the signal audio was rated by the lab experts. For those multipath tests where no impairment was heard, noise was added in 0.5 dB steps until the TOA and POF were found. The numerical results of the tests are in Desired/Undesired (D/U) signal ratios. These tests were recorded and sent to the CRC for further assessment.

If multipath impairments were heard by the laboratory experts without noise added, Expert Observation and Commentary (EO&C) tests were conducted by the transmission laboratory experts. The scale for the EO&C tests is shown in the table.

Co-Channel, First and Second Adjacent Without Multipath

These tests measured the Digital to Digital interference to co-channel, first adjacent, and the second adjacent. The adjacent channel tests were conducted on both the lower and upper channels. The undesired signal was increased in 0.5 dB steps until the TOA and POF were heard by the laboratory specialists. The EBU SQAM disc glockenspiel was used for the test audio. For the Inband-On/Channel (IBOC) systems, the composite signal was used. The EO&C tests were conducted by the transmission laboratory specialists. The D/U at the TOA and POF is reported for each system. Table #4 shows the results of these tests.

Co-Channel, First, and Second Adjacent Channels with Multipath

These tests measured the Digital to Digital interference to co-channel, lower first adjacent, and lower second adjacent. The undesired signal was increased in 0.5 dB steps until the TOA and POF were heard by the laboratory specialists. If interference was heard without undesired signal added, no additional assessments were conducted. Glockenspiel was used for the test audio. The D/U at the TOA and POF is reported.

Tables #5, #6, and #7 show the results of the interference tests with multipath. The assessments were completed by the specialist at the transmission laboratory.

Re-Acquisition

Noise was added to the signal in 0.25 dB steps until POF. At POF the attenuator setting was recorded. The DAR transmitter was then disconnected from the receiver for at least 30 seconds to assure loss of lock. The signal was then reconnected to the DAR receiver and acquisition time recorded. Acquisition is the reproduction of usable music. Mozart track 67 of the EBU SQAM disc was used. The test was conducted three times with the noise set at 2 dB, 4 dB, and 6 dB below POF. At each noise level the test was conducted five times, and the results were averaged. The results of the re-acquisition tests with simulated multipath are not included in this document.

Table 8 shows the average results of the five tests in seconds. POF-2, POF-4, and POF-6 represent the signal levels below POF. The assessments were completed by the specialist at the transmission laboratory.

GAUSSIAN NOISE

	GLOCKENSPIEL		SOPRANO		CLARINET	
PROPONENT	C_o/N_o dB TOA	C_o/N_o dB POF	C_o/N_o dB TOA	C_o/N_o dB POF	C_o/N_o dB POF	C_o/N_o dB TOA
A E-147 224 Kb/s	8.48	5.98	8.23	6.23	8.98	6.48
B E-147 193 Kb/s	8.46	5.96	8.71	6.21	8.96	6.46
C AT&T	11.36	10.61	11.11	10.36	11.11	10.36
D LSB AT&T/AMATI	18.85	16.85	17.60	16.35	18.10	16.60
E DSB AT&T/AMATI	10.76	9.51	10.51	9.51	10.76	9.51
F JPL VOA	3.26	2.26	3.26	2.26	3.26	2.51
G FM2 USADR	25.10	21.60	25.10	21.35	26.35	22.35
H FM1 USADR	10.51	8.51	10.01	8.51	10.51	8.51
I AM USADR	19.64	17.14	19.64	17.64	19.89	17.89
K DSB AT&T/AMATI	10.29	8.79	10.04	8.79	10.04	8.79
L FM1 USADR	11.33	6.33	10.83	6.83	11.08	6.58

Table 1

CO-CHANNEL

PROPONENT	GLOCKENSPIEL		SOPRANO		CLARINET	
	D/U	D/U	D/U	D/U	D/U	D/U
	dB	dB	dB	dB	dB	dB
	TOA	POF	TOA	POF	POF	TOA
A E-147 224 Kb/s	8.60	5.85	8.35	5.85	8.35	5.85
B E-147 193 Kb/s	8.50	6.00	8.25	6.00	8.50	6.00
C AT&T	11.64	10.64	11.39	10.64	11.64	10.64
D LSB AT&T/AMATI	17.40	15.90	17.15	15.65	17.40	15.90
E DSB AT&T/AMATI	11.12	9.12	10.87	9.37	10.87	9.37
F JPL VOA	5.50	4.50	5.25	4.50	5.50	4.50
G FM2 USADR	42.60	38.60	41.10	38.60	42.60	39.10
H FM1 USADR	11.37	7.87	10.87	7.37	10.87	6.87
I AM USADR	25.98	23.73	26.23	23.73	26.73	24.23
K DSB AT&T/AMATI	10.26	8.76	9.76	9.01	10.01	9.01
L FM1 USADR	11.04	6.04	10.54	6.04	11.04	6.79

Table 2

MULTIPATH SUMMARY (RAYLEEIGH)

	URBAN SLOW			URBAN FAST			RURAL FAST			TERRAIN OBSTRUCTED		
PROPONENT	GLOCK	SOPRANO	CLARINET	GLOCK	SOPRANO	CLARINET	GLOCK	SOPRANO	CLARINET	GLOCK	SOPRANO	CLARINET
A E-147 224 Kb/s	20 12	18 13	19 12	15 10	15 10	15 10	EOC-1	EOC-1	EOC-1	15 9	14 9	15 9
B E-147 192 Kb/s	19 13	19 13	19 13	18 10	18 10	16 9	EOC-1	EOC-1	EOC-1	15 9	15 9	15 9
C AT&T	29 22	29 22	29 22	24 18	24 18	23 18	EOC-1	EOC	EOC	EOC-1	EOC-1	21 18
D LSB AT&T/AMATI	EOC-1	EOC-1	EOC-1	EOC-1	EOC-1	EOC-1	EOC-1	EOC-1	EOC-1	EOC-2	EOC-2	EOC-2
E DSB AT&T/AMATI	EOC-1	EOC-1	EOC-1	23 18	22 16	22 16	25 18	24 18	24 18	EOC-1	EOC-1	EOC-1
F JPL VOA												
G FM2 USADR	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3
H FM1 USADR	EOC-1	EOC-1	EOC-1	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3	EOC-3
K DSB AT&T/AMATI	31 21	30 21	30 21	20 16	20 16	20 16	20 16	20 16	20 16	21 17	20 16	21 16
L FM1 USADR	EOC-1	EOC-1	EOC-1	28 14	25 14	28 14	EOC-1	EOC-1	EOC-1	EOC-1	EOC-1	EOC-1

BLOCKS WITH NUMBERS:

LEFT NUMBER TOA Co/No dB

RIGHT NUMBER POF Co/No dB

EOC RATING SCALE (NO NOISE ADDED)

0. NO IMPAIRMENT
1. SHORT OR SMALL IMPAIRMENTS
2. MANY OR CONTINUOUS IMPAIRMENTS
3. AUDIO FAILURE

F. JPL/VOA TESTS USED RICIAN MODEL

I. USADR AM USED A DIFFERENT TEST

Table 3

CO-CHANNEL, FIRST AND SECOND ADJACENT

GLOCKENSPIEL

PROPONENT	CO-CHANNEL		LOWER 1ST		UPPER 1ST		LOWER 2ND		UPPER 2ND	
	D/U dB TOA	D/U dB POF	D/U dB TOA	D/U dB POF	D/U dB TOA	D/U dB POF	D/U dB TOA	D/U dB POF	D/U dB TOA	D/U dB POF
A E-147 224 Kb/s	9.23	7.23	-33.02	-34.02	-32.77	-33.77	NT	NT	NT	NT
B E-147 192 Kb/s	8.98	6.73	-33.02	-34.27	NT	NT	NT	NT	NT	NT
C AT&T	11.40	10.40	-15.35	-15.85	-17.85	-18.60	-23.85	-23.85	-23.85	-23.85
D LSB AT&T/AMATI	16.99	15.49	42.72	38.72	NT	NT	-16.78	-19.53	2.22	-2.28
E DSB AT&T/AMATI	10.72	9.47	31.47	29.47	31.31	29.31	-15.47	-19.47	SYM	SYM
F JPL VOA	5.50	4.75	-14.25	-15.00	-13.00	-14.25	NT	NT	NT	NT
G FM2 USADR	44.31	40.81	30.06	28.81	30.31	29.06	SYM	SYM	30.56	NT
H FM1 USADR	11.96	7.46	31.46	19.46	31.21	19.21	9.46	1.21	SYM	SYM
I AM USADR	26.75	23.75	32.75	29.00	31.75	28.00	31.25	28.25	SYM	SYM
K DSB AT&T/AMATI	10.46	8.96	23.96	20.46	24.21	20.21	-16.79	-20.54	-18.04	-21.79
L FM1 USADR	10.78	7.28	27.28	22.78	26.78	22.78	3.78	-4.78	5.28	-1.47

TEST PROCEDURES DID NOT CALL FOR SECOND ADJACENT TESTS FOR SYSTEMS A, B, + F (NT)

A SINGLE SECOND ADJACENT TEST WAS CONDUCTED ON SYSTEMS THAT DISPLAYED 1ST ADJACENT SYMMETRY

Table 4

CO-CHANNEL WITH MULTIPATH (RAYLEIGH0

GLOCKENSPIEL

WITH COMPOSITE OFFSETS

	URBAN SLOW		URBAN FAST		RURAL FAST		TERRAIN OBSTRUCTED	
PROPONENT	TOA D/U dB	POF D/U dB	TOA D/U dB	POF D/U dB	TOA D/U dB	POF D/U dB	TOA D/U dB	POF D/U dB
A E-147 224 Kb/s	15.90	10.40	14.40	8.40	*	*	12.15	7.15
B E-147 192 Kb/s	19.44	11.69	14.44	8.44	*	*	14.44	7.94
C AT&T	33.71	23.96	32.71	21.96	*	*	*	*
D LSB AT&T/AMATI	*	*	*	*	*	*	*	*
E DSB AT&T/AMATI	*	*	26.26	20.76	*	*	*	*
F JPL VOA	NA	NA	NA	NA	NA	NA	NA	NA
G FM2 USADR	*	*	*	*	*	*	*	*
H FM1 USADR	*	23.88	*	*	*	*	*	*
K DSB AT&T/AMATI	32.06	19.06	18.06	15.06	20.06	16.06	22.06	17.06
L FM1 USADR	*	*	27.03	14.03	*	*	*	*

*NO CO-CHANNEL ADDED

Table 5

LOWER 1ST ADJACENT WITH MULTIPATH (RAYLEIGH)

GLOCKENSPIEL

WITH COMPOSITE OFFSETS

	URBAN SLOW		URBAN FAST		RURAL FAST		TERRAIN OBSTRUCTED	
PROPONENT	TOA D/U dB	POF D/U dB	TOA D/U dB	POF D/U dB	TOA D/U dB	POF D/U dB	TOA D/U dB	POF D/U dB
A E-147 224 Kb/s	-15.35	-18.96	-18.87	-27.87	24.88	24.88	-15.96	-17.88
B E-147 192 Kb/s	6.06	6.06	5.94	5.94	*	*	5.94	5.94
C AT&T	1.71	6.29	-0.79	4.21	*	*	*	*
D LSB AT&T/AMATI	*	*	*	*	*	*	*	*
E DSB AT&T/AMATI	*	*	41.76	32.76	*	*	*	*
F JPL VOA	NA	NA	NA	NA	NA	NA	NA	NA
G FM2 USADR	*	*	*	*	*	*	*	*
H FM1 USADR	*	37.88	*	*	*	*	*	*
K DSB AT&T/AMATI	45.21	28.21	31.21	24.21	31.21	23.21	33.21	23.21
L FM1 USADR	*	*	45.02	30.02	*	*	*	*

* NO ADJACENT CHANNEL ADDED

Table 6

LOWER 2ND ADJACENT WITH MULTIPATH (RAYLEIGH)

GLOCKENSPIEL

WITH COMPOSITE OFFSET

	URBAN SLOW		URBAN FAST		RURAL FAST		TERRAIN OBSTRUCTED	
PROPONENT	TOA D/U dB	POF D/U dB	TOA D/U dB	POF D/U dB	TOA D/U dB	POF D/U dB	TOA D/U dB	POF D/U dB
A E-147 224 Kb/s	NT	NT	NT	NT	NT	NT	NT	NT
B E-147 192 Kb/s	NT	NT	NT	NT	NT	NT	NT	NT
C AT&T	-14.04	-14.04	-14.04	-14.04	*	*	*	*
D LSB AT&T/AMATI	NT	NT	NT	NT	NT	NT	NT	NT
E DSB AT&T/AMATI			1.51	6.51	*	*	*	*
F JPL VOA	NA	NA	NA	NA	NA	NA	NA	NA
G FM2 USADR	*	*	*	*	*	*	*	*
H FM1 USADR	*	16.38	*	*	*	*	*	*
K DSB AT&T/AMATI	8.21	5.21	6.21	-1.79	-7.79	1.21	0.79	2.21
L FM1 USADR	*	*	29.99	11.99	*	*	*	*

*NO ADJACENT CHANNEL ADDED

NOTE: FOR AT&T URBAN SLOW AND FAST INSUFFICIENT UNDESIRED SIGNAL WAS AVAILABLE

Table 7

RE-ACQUISITION

	AVERAGE TIME IN SECONDS		
PROPONENT	POF-2	POF-4	POF-6
A E-147 224 Kb/s	1.00	1.00	1.00
B E-147 192 Kb/s	1.00	1.00	1.00
C AT&T	1.00	1.00	1.00
D LSB AT&T/AMATI	2.60	2.80	1.40
E DSB AT&T/AMATI	2.60	3.60	3.20
F JPL VOA	1.20	2.60	1.00
G FM2 USADR	4.20	5.60	4.20
H FM1 USADR	5.80	5.60	5.40
I AM USADR	4.40	3.40	3.60
K DSB AT&T/AMATI	3.60	2.60	3.80
L FM1 USADR	9.40	7.20	5.60

Table 8

Appendix 4

Summary of In-Band Terrestrial System Laboratory Test Results

Abstract

The Electronic Industries Association Consumer Electronic Manufacturers Association (EIA/CEMA) Subcommittee on Digital Audio Radio has completed the laboratory tests for seven digital sound broadcasting systems for digital radio systems. Of these, four systems operate in the VHF 88-108 MHz FM band, one in the MF band (AM), one in the satellite band, and one in a new terrestrial DAR band (L-band). Of the four systems intended to operate in the FM band, one is designed to operate on adjacent (or-unused) channels (IBAC), and the remaining three are intended to share existing channels. The In-Band/On-Channel (IBOC) DAR system laboratory tests were conducted in collaboration with the National Radio Systems Committee.

This paper is intended to focus only on the tests of FM band IBOC and IBAC systems and only on those tests that effect the performance of the digital signal and in-band compatibility. Audio quality, multipath performance or subcarrier performance will be dealt with elsewhere. The complete laboratory test results for all seven systems is available from EIA (1).

Introduction

The DAR tests were conducted in two laboratories, the transmission laboratory at NASA Lewis Research Center, Cleveland, Ohio and the expert subjective tests at the Communications Research Centre (CRC), Ottawa, Ontario. The tests at NASA were in two phases, digital and in-band compatibility. The digital phase evaluated the signal quality and failure characteristics. Additionally, the digital test included multipath, co-channel, and adjacent channel impairments. The in-band compatibility phase of the transmission tests included a series of tests to measure possible interference to the existing analog program service caused by the introduction of the in-band DAR signal. Comprehensive tests were also conducted to measure possible interference to the ancillary subcarrier service channels by the in-band DAR signal. The in-band compatibility tests used a group of receivers selected as representative of the existing analog consumer receiver population.

The NASA laboratory digital tests were conducted using subjective detection of the Threshold Of Audibility (TOA) and Point Of Failure (POF) by the laboratory specialists. The results of the signal failure characterization transmission tests were digitally recorded and assessed by a larger group of experts at CRC.

In-band compatibility objective tests were conducted at the transmission laboratory. Digital audio recordings were made at the output of the analog compatibility receivers for subjective evaluation by a group of industry experts.

Testing

The laboratory test plans were previously reported. Three FM band IBOC and one IBAC systems offered by proponents for testing are shown in Table 1 with the location of the digital signal.

System Waveform

The IBOC systems differ in the location of the digital signal in the FM channel.

The AT&T/Lucent/Amati Double SideBand (DSB) mode places the digital signals on both sides of the FM signal using the first 100 kHz of the first upper and lower adjacent channel, see Figure 1A. Each digital sideband is 73.5 kHz wide for a total digital bandwidth of 147 kHz. The total composite channel bandwidth is 400 kHz.

The USADR FM-1 system digital signal is also located in the upper and lower first adjacent channel. Figure 1C shows that the digital signal extends 120 kHz into the first adjacent channel. The half power bandwidth of each digital signal is 100 kHz for a total digital bandwidth of 200 kHz. The FM-1 system total composite channel bandwidth is 440 kHz. Both the AT&T/Amati and the FM-1 system's digital signal is not an FM subcarrier, but is broadcast from a second transmitter and passively combined with the FM analog signal.

The IBOC proponents maintain that the digital sideband signals are within the guidelines established by FCC 73.317 (2) of the FCC code. This rule states that "Any emission appearing on a frequency removed from the carrier by between 120 kHz and 240 kHz inclusive must be attenuated at least 25 dB below the level of the unmodulated carrier".

The AT&T/Amati system is capable of operating in three modes; double sideband (DSB) Figure 1A, Lower SideBand (LSB) Figure 1B, and Upper SideBand (USB). The LSB and USB modes are designed to be used to alleviate known adjacent channel interference. The receiver will automatically select the transmitted mode. The DSB and LSB modes were tested.

The digital signal for the USADR FM-2 system is designed to be completely orthogonal to the host analog FM. A spectrum analyzer plot of the composite signal is shown in Figure 1D. The digital energy is transmitted under the analog and spreads into the adjacent channels at a decreasing level.

The AT&T/Amati and the USADR FM-1 IBOC performance data in this document is from the systems as re-tested with system modifications.

The AT&T/Lucent IBAC system transmits the digital signal in a single 200 kHz channel. A spectrum analyzer plot of the signal is shown in Figure 1E.

Digital to Digital Interference Tests

The digital -> digital tests were designed to determine the coverage for each in-band system operating in the FM band environment. The (digital to digital) tests were conducted on co-channel and first and the second adjacent channels.

The Desired/Undesired (D/U) ratios for the composite IBOC signal can be used to calculate the digital signal coverage. Because the FM band D/U ratios have been set by FCC rules, the D/U ratios for the FM IBOC system have already been established.

A second digital transmitter or system simulator was used to simulate interference from a second digital station with a waveform matching the system under test.

For the subjective digital transmission tests, the undesired signal was added to the desired signal and increased in amplitude in 0.25 dB steps until the TOA and POF were heard by the laboratory specialists listening to the digital audio. The D/U was recorded at this point. Glockenspiel was used for this series of tests as the critical audio program material.

Tables 2, 3, and 4 show the performance of each system for the three interference modes. Each system's D/U for POF is shown and a comparison is made between the laboratory D/U and that permitted by the FCC rules. Simulated multipath tests were also conducted that showed an increase in interference with multipath.

Co-channel IBOC digital performance at the POF exceeds the FCC 20 dB D/U requirement at the protected contour by 11 db for the Amati/AT&T DAR system and by 14 dB for the USADR FM-1 system. The AT&T/Amati LSB system was 3 dB better, and the FM-2 system was 44.3 dB poorer than the FCC 20 dB D/U (Table 2). The AT&T/Lucent IBAC system exceeded the FCC requirement by 9.6 dB.

First Adjacent digital performance for all IBOC systems did not meet the FCC 6 dB D/U criteria. Both the AT&T/Amati and the FM-1 systems were below the FCC D/U by at least 14 dB at POF. Figure 1 shows that the principal interferer for the sideband IBOC systems is the adjacent channel FM signal. With the side band IBOC systems, the digital signal is 15 dB lower than the interfering FM signal (Figures 1A & 1C). The laboratory tests have shown that the co-channel D/U ratios of about 10 dB at TOA can be expected for non-IBOC and IBOC systems. If we add the 10 dB D/U for the co-channel and the 15 dB D/U for the IBOC analog to digital power ratio, we have a predicted 25 dB D/U at TOA for IBOC -> IBOC first adjacent interference. The D/U performance of

AT&T/Amati system of 24 dB exceeds this predicted D/U by 1 dB. This difference may be explained by the fact that the interferer is the analog signal of the composite undesired IBOC effecting only one half of the desired digital signal (Table 3).

The IBAC first adjacent performance exceeded FCC requirements by 23.2 dB.

Second Adjacent D/U ratios are important for the sideband IBOC systems because the digital signal is located in the adjacent channel. With the present FCC rules, contour protection is defined as -40 dB D/U (2). The AT&T/Lucent/Amati DSB system D/U at POF was 19 dB below (more sensitive to interference) the FCC 40 dB protection criteria, and the USADR/FM-1 D/U at POF 37 dB below this criteria (Table 4). The AT&T/Lucent IBAC system D/U at POF was 23.2 dB above (less sensitive to interference) the FCC criteria.

FM to Digital Interference Tests

Interference from the analog FM to the composite IBOC digital tests were conducted for co-channel, lower first adjacent, upper first adjacent, lower second adjacent, upper second adjacent, and simultaneous lower and upper second adjacent.

The IBOC systems that use the adjacent channel for the transmission of the IBOC digital audio had negative D/U ratios for the co-channel tests. This extraordinary co-channel result can be explained by the fact that the undesired FM station only interferes with the host FM (Figures 1A & 1C).

The FM -> IBOC first adjacent channel tests show slightly less interference from the FM signal than the considerable interference found in the IBOC -> IBOC tests. Eliminating the digital signal from the host FM had a slight effect on the interference experienced in the IBOC -> IBOC tests.

The second adjacent test results show very little interference from the analog to the digital for those systems that used the adjacent channel for digital. The AT&T/Amati DSB system came within 2 dB of meeting the FCC -40 dB D/U at POF.

FM-to-FM Reference Tests

To establish a reference for the inband compatibility tests, it was necessary to conduct a series of FM -> FM D/U tests with a representative group of contemporary consumer FM stereo radios. Five FM radios were selected that represent a cross section of receivers in use in the United States. The selection was divided into four categories: auto, portable, high end home Hi-Fi, and competitive Hi-Fi. The two automobile radios were selected because of their large population and their wide difference in the stereo blend. These auto radios also showed high adjacent channel rejection. The portable and personal portable use similar circuitry and have less adjacent channel rejection. The high end home Hi-Fi radios had good 2nd adjacent channel rejection, but exhibited the similar first adjacent channel rejection characteristics found in the portable and home radios.

Table 5 shows the result of the FM -> FM D/U tests that were conducted with the five radios. For the D/U measurements, the undesired signal RF level was set for a 45 dB audio signal-to-noise ratio. The audio noise measurement was made using quasi-peak detection, a 15 kHz low pass filter, and the CCIR filter. The desired signal level was -62 dBm. Antenna matching networks were used when needed. The portable and home receivers were tested in a shielded box that eliminated interference from other electronic devices in the laboratory. The two auto radios did not need additional shielding.

IBOC-to-Host FM Compatibility Tests

The objective of this test was to measure possible interference from the IBOC digital transmitter to a cross section of consumer analog receivers that are tuned to the host FM station. The tests were conducted at strong (-47 dBm) and weak (-77 dBm) signal levels. For reference the test receiver signal to noise ratio was measured with the laboratory transmitter (Harris THE-1). The IBOC digital signal was turned on, and the audio RMS S/N measured. Changes in S/N were then noted (Table 6).

Special Testing: There are many ways of decoding the FM stereo signal. In practice the PLL stereo decoder has become the norm. Because the PLL stereo decoder uses square wave switching, the circuit is able to demodulate baseband signals which are the odd harmonics of 38 kHz, 114 kHz and 190 kHz (3). Without 114 kHz low pass filters or special circuitry, the PLL decoders will detect the IBOC digital signal as noise. To further understand this phenomena, a special receiver test was conducted at the laboratory to find out which receivers were sensitive to the 114 kHz signal without using a DAR signal. A CW subcarrier was added to the FM signal at 113 kHz with 10% injection, and the receiver audio output noise measured. Receivers #2, #3, and #4 exhibited a large increase in noise with the 113 kHz subcarrier. This noise was the beat tone of 1 kHz between the test signal of 113 kHz and 114 kHz. Table #6 shows the results of the IBOC-to-host FM and 113 kHz subcarrier test for the five laboratory radios. The test showed that the radios that have a significant increase in noise with the IBOC signal also had an increase in noise with the 113 kHz subcarrier test. The sensitive radios had noise increases of 18 dB to 26 dB with the IBOC signals. The two auto radios that did not have a noise increase with IBOC did not have an audio noise increase with the 113 kHz subcarrier test.

Extended CW subcarrier tests conducted using a 189 kHz subcarrier revealed that the radios were also sensitive to 190 kHz. Injecting a signal at 152 kHz midway between the 114 kHz and 190 kHz did not change the radios output noise level. It appears that the band of frequencies around 152 kHz does not effect the noise performance of the PLL stereo receiver.

Subjective impairment tests were also conducted with expert listeners. The audio output of each of the five FM radios was recorded on digital audio tape, and these tapes were transferred to eight CDs for subjective assessment of digital-to-host FM, digital-to-FM co-channel, first adjacent, and second adjacent channel tests. Eleven experts then compared the FM signal audio to the IBOC FM signal audio and rated the impairments using the seven point numerical scale. The results showed that the experts rated the 40 to 50 dB RMS S/N ratios worse to much worse than the reference. The S/N degradation results shown in Table 6 were consistent with the observed degradation.

Digital-to-FM Interference Tests

A comprehensive set of compatibility tests were conducted for co-channel, first adjacent channel, and second adjacent channel Digital -> FM interference. All five of the selected consumer radios were used. The first step for the objective tests was to establish an FM-to-FM reference by adjusting the undesired FM RF signal level for an audio S/N of 45 dB at the test radio output. The undesired FM signal was then replaced with the composite IBOC or IBAC signal, and the undesired level was adjusted for a 45 dB audio S/N. The test results in Table 7 compare the D/U ratios for the reference FM -> FM tests (existing service) to the D/U ratios for the digital -> FM tests. A positive increase in D/U indicates an interference increase. The objective test results were supplemented with expert laboratory observation and commentary, and additional subjective listening tests were conducted by industry experts. (not reported here).

The digital to analog co-channel test results show little difference in interference between the FM -> FM tests and the digital -> FM tests.

The first adjacent tests were conducted at a reference 35 dB and 45 dB audio S/N ratios. Because receivers #3 and #4 are not as selective as the auto radios, the first adjacent FM interference masked additional interference from the IBOC signal. During the test that used a 35 dB audio S/N, receivers #2 and #5 displayed an increase in IBOC interference. Receiver #5 is very selective and is able to detect FM or digital signals transmitted in the first adjacent channel well beyond the FCC protected contour. For the 35 dB S/N tests only, receivers #2 and #5 showed an increase in digital interference.

For the second adjacent channel tests four of the radios had an increase in interference. With the close spacing of the second adjacent channels, this interference can be significant.

CONCLUSIONS

Digital-to-Digital

The IBOC systems that use the first adjacent channel for the transmission of the digital signal have a fundamental problem with the interference from the undesired first adjacent

FM channel that will result in a significant reduction of digital coverage as compared to the host FM. The second adjacent interference is critical, but can be improved by system design. With the exception of the system that transmits the digital signal under the analog, the co-channel performance exceeded the FCC prescribed D/U ratios (less interference).

FM-to-Digital

Again, the systems that transmit the digital signal in the first adjacent channel have a significant problem with interference from an undesired FM signal in first adjacent channel. These systems experienced little interference from FM stations operating on co-channel or second adjacent channels.

Digital-to-FM

An increase in interference to other FM stations operating on the first or second adjacent channels was found. This increase is receiver dependent.

IBOC-to-FM Host

This interference is most pronounced at moderate to strong RF signal levels. The noise is detected by PLL stereo decoders and can be eliminated with the use of special circuitry. A large population of stereo receivers are subject to this noise increase.

System Design

AT&T/Amati and the USADR FM-1 systems were updated by the proponents in the spring of 1995 prior to the start of the second round of digital performance tests.

References

1. Digital Audio Radio Laboratory Tests Report, Transmission Quality Failure Characterization and Audio Compatibility, Published by the Electronic Industries Association, CEMA, August 11, 1995.

2. Code of Federal Regulations, Part 73 Radio Broadcast Services

3. NAB Engineering Handbook, Seventh Edition, Section 3.4 Subcarrier Transmission and Stereophonic Broadcasting, Page 3.4-121 Stereo Decoder Circuits, Author, John Kean.

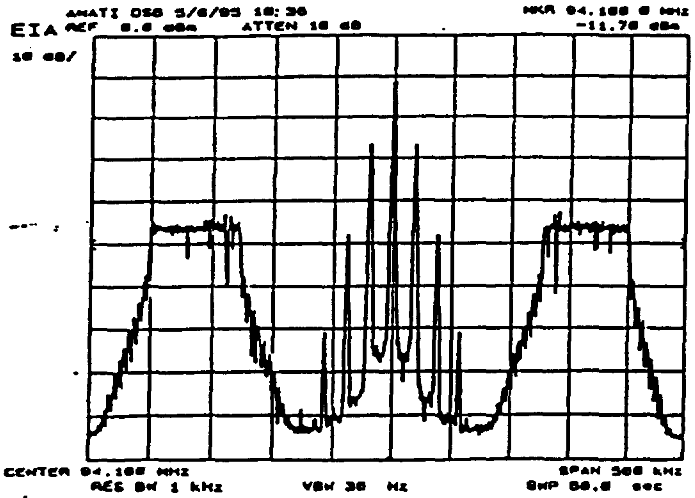


Figure 1A. AT&T/Amati DSB

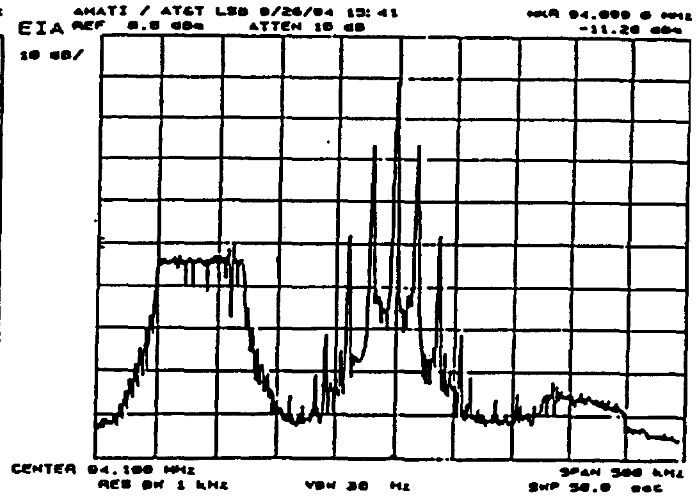


Figure 1B. AT&T/Amati LSB

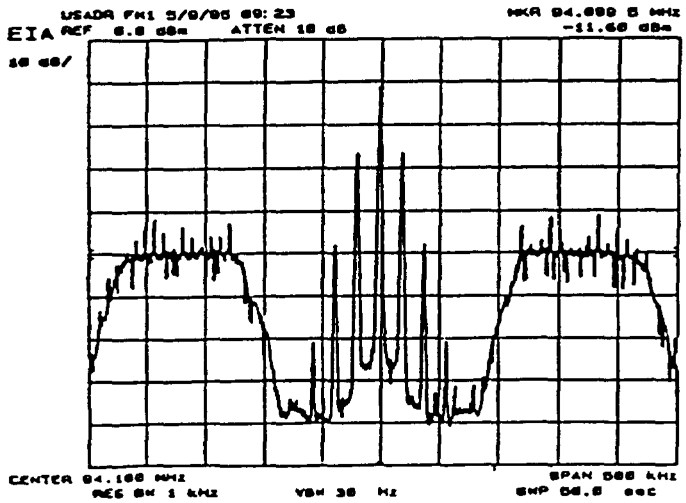


Figure 1C. USADR FM-1

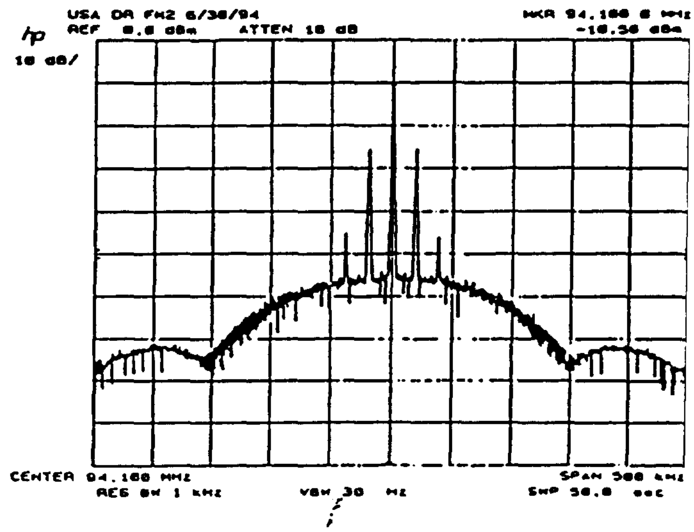


Figure 1D. USADR FM-2

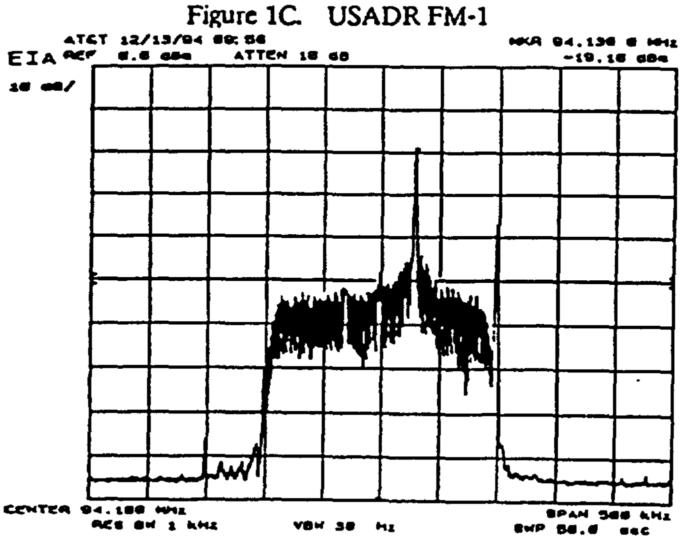


Figure 1E AT&T IBAC

Table 1. IBOC Systems	
Proponent	Description
AT&T/Amati Mode 1	Dual Side Band
AT&T/Amati Mode 2	Lower Side Band
USADR-FM 1	Dual Side Band
USADR-FM 2	Under FM

Table 2. IBOC/IBAC Co-Channel D -> D Laboratory Test Results Results are for TOA and POF					
	Amati/AT&T DSB D/U	Amati/AT&T LSB D/U	USADR FM-1 D/U	USADR FM-2 D/U	AT&T/Lucent
TOA	10.5 dB	17 dB	10.8 dB	44.3 dB	11.4 dB
POF	9.0 dB	15.5 dB	7.3 dB	40.8 dB	10.4 dB
POF Compared to FCC 73.215 or 20 dB D/U	11.0 dB Less Sensitive to Interference	4.5 dB Less Sensitive to Interference	13.7 dB Less Sensitive to Interference	20.8 dB More Sensitive to Interference	9.6 dB Less Sensitive to Interference

FCC 73.215 Contour protection for short-spaced assignments.

Table 3. IBOC/IBAC First Adjacent D -> D Laboratory Test Results					
	Amati/AT&T DSB D/U	Amati/AT&T LSB D/U	USADR FM-1 D/U	USADR FM-2 D/U	AT&T/Lucent
TOA	24.1 dB	42.7 dB	27.0 dB	30.2 dB	-16.6 dB
POF	20.3 dB	38.7 dB	22.8 dB	29.0 dB	-17.2 dB
POF Compared with FCC 73.215 or 6 dB D/U	14.3 dB More Sensitive to Interference	32.7 dB More Sensitive to Interference	16.8 dB More Sensitive to Interference	23.0 dB More Sensitive to Interference	23.2 dB less Sensitive to Interference

The tests were done on the upper and lower first adjacent channels and the results averaged.
FCC 73.215 Contour protection for short-spaced assignments.

Table 4	IBOC/IBAC Second Adjacent D -> D Laboratory Test Results				
	Amati/AT&T DSB D/U	Amati/AT&T LSB D/U	USADR FM-1 D/U	USADR FM-2 D/U	AT&T/Lucent D/U
TOA	-17.4 dB	-16.8 dB Lower 2.2 dB Upper	4.5 dB	30.6 dB	-23.85 dB Test Bed Limit (no TOA)
POF	-21.2 dB	-19.5 dB Lower -2.3 dB Upper	-3.1 dB	No Test	-23.85 dB Test Bed Limit (no POF)
POF Compared with FCC 73.215 or -40 dB D/U	18.8 dB More Sensitive to Interference	14.8 dB Lower 37.7 dB Upper More Sensitive to Interference	36.9 dB More Sensitive to Interference	70.6 dB More Sensitive to Interferen ce (this is TOA)	For the A -> D test the TOA was -45 dB System should exceed FCC by at least 5 dB

Unless otherwise indicated the tests were done on the upper and lower second adjacent channels and the results averaged.
FCC 73.215 Contour protection for short-spaced assignments.

Table 5	REFERENCE FM to FM RECEIVER TESTS				
Receiver	Type	Co-Channel D/U dB.	1 st Adjacent D/U dB	2 nd Adjacent D/U dB	113 kHz Test S/N dB
1. Delco	Auto	36.2	4.7	-45.0	No Change
2. Denon	Hi-Fi	43.4	18.0	-28.9	34.0
3. Panasonic	Portable	40.9	27.3	-10.1	33.6
4. Pioneer	Hi-Fi	44.2	26.6	-15.0	33.1
5. Ford	Auto	35.2	-6.1	-45.3	No Change

For the D/U measurements, the interfering FM signal level was set for a 45 dB audio S/N. This measurement was made using quasi-peak detection, a 15 kHz LP filter, and the CCIR filter.

The upper and lower adjacent D/Us were averaged.

Table 6.	IBOC DAR -> Host FM RMS Noise Signal Level -47 dBm				
Receiver	Type Radio	S/N FM Only Reference	S/N. 114 kHz Test	S/N AT&T/Amati DSB	S/N USADR FM-1
1. Delco 161924463	Auto	60.0 dB	No Change	60.7 dB	60.3 dB
2. Denon TU-280RD	Hi-Fi High end	68.0 dB	34.0 dB	50.0 dB	44.9 dB
3. Panasonic RX-PS430	Stereo Portable	67.5 dB	33.6 dB	44.2 dB	42.0 dB
4. Pioneer SX-201	HI-Fi	66.0 dB	33.1 dB	40.0 dB	39.2 dB
5. Ford F4XF-19B132-CB	Auto	65.0 dB	No Change	64.0 dB	62.7 dB

Table 7.	Digital -> ANALOG INTERFERENCE					
Receivers		Delco #1 D/U in dB	Denon #2 D/U in dB	Panasonic #3 D/U in dB	Pioneer #4 D/U in dB	Ford #5 D/U in dB
Co-Channel Audio S/N 45 dB	Reference	36	43	41	44	35
	AT&T	36	43	41	44	35
	AT&T Amati	37	43	41	44	35
	USADR FM-1	35	43	41	44	35
First Adjacent Audio S/N 45 dB	Reference	5	18	27	27	-6
	AT&T	8	27	32	32	15
	AT&T Amati	20	28	30	31	19
	USADR FM-1	18	26	29	30	17
First Adjacent Audio S/N 35 dB	Reference	4	7	15	15	-17
	AT&T	6	16	20	21	-17
	AT&T Amati	8	17	18	20	8
	USADR FM-1	7	15	17	18	6
Second Adjacent Audio S/N 45 dB	Reference	-24	-29	-10	-15	-45
	AT&T	-24	-8	-6	-7	-17
	AT&T Amati	-24	-19	-5	-3	-30
	USADR FM-1	-24	-10	2	4	-27

The undesired signal level was set for either 35 dB or 45 dB audio S/N ratio. The audio noise measurements were made using quasi-peak detection, a 15 kHz filter, and the CCIR filter.
The first and second D/U ratios are the averaged upper and lower D/U measurements.

Appendix 5

Measured Analog FM Signal Levels and Impact on In-band Digital Audio Broadcasting Implementation

Introduction

Measurements were made at several locations of FM broadcast signal levels throughout the 88-108 Mhz FM band to determine existing spectrum occupancy with particular attention to signal ratios with varied signal adjacencies. These measurements illustrate the importance of minimizing adjacent channel interference in the design of in-band DAR systems.

Methods

Measurements were made from a parked automobile with a 1/4 wave vertical antenna mounted on the roof (four feet above road). The FM receiver's seek tuning mode was used for station selection. In the seek mode the receiver stopped for signals as low as -76 dBm at the receiver input. At this signal level the test receiver was in full blend (no stereo). Only the data from listenable signals was used (CCIR impairment level of 3, slightly annoying). Enclosed are representative graphs and tables showing the results of measurements at four sites (Table 1 through 4 and Graph 1 through 4) selected from a field of 38 chosen to illustrate potential adjacent channel interference to digital reception in congested areas.

Discussion

The performance of in-band DAB systems depends greatly on the specific protection ratios for the first and second adjacent channels, as measured at the input terminals of the DAR receiver. Because FM band analog transmitting power levels are set by regulatory limits, analysis of band-wide signal level measurements at fixed locations will show the expected performance for DAB systems with adjacent channel interference.

Adjacent channel interference to the FM receivers (digital-to-analog) depends on the receiver characteristics and the protection ratios. Noise caused by in-band/on-channel (IBOC) digital signals to the host FM station is dependent on the IBOC system design and the analog receiver characteristics.

Analysis

The following is a proposed procedure for analyzing the performance of an in-band system using the signal level measurements. The D/U characteristics of the AT&T/Lucent Technologies/Amati dual side-band system is used for the sample. The final modified version of this system was submitted for testing in the spring of 1995.

Laboratory Test Results

1) first adjacent channel -- Without multipath the digital-to-digital laboratory tests measured a 24 dB Desired/Undesired (D/U) protection ratio at the Threshold of Audibility (TOA). Using the least aggressive multipath scenarios, the TOA D/U averaged 30 dB.

2) second adjacent channel -- Without multipath the digital-to-digital laboratory tests measured a -17.5 dB D/U at the TOA. With multipath the D/U averaged 0 dB.

Sample Analysis

Using these D/U figures (30 dB and 0 dB) for TOA, four measurement sites were analyzed; the results are presented in Table 5.

Site # State	#FM stations received	1st adj. stations above TOA	2nd adj. stations above TOA
7 VA	35	26	25
10 MD	38	33	25
17 MD	47	26	31
10 NJ	47	14	31

TABLE 5
Number of FM station signals above TOA

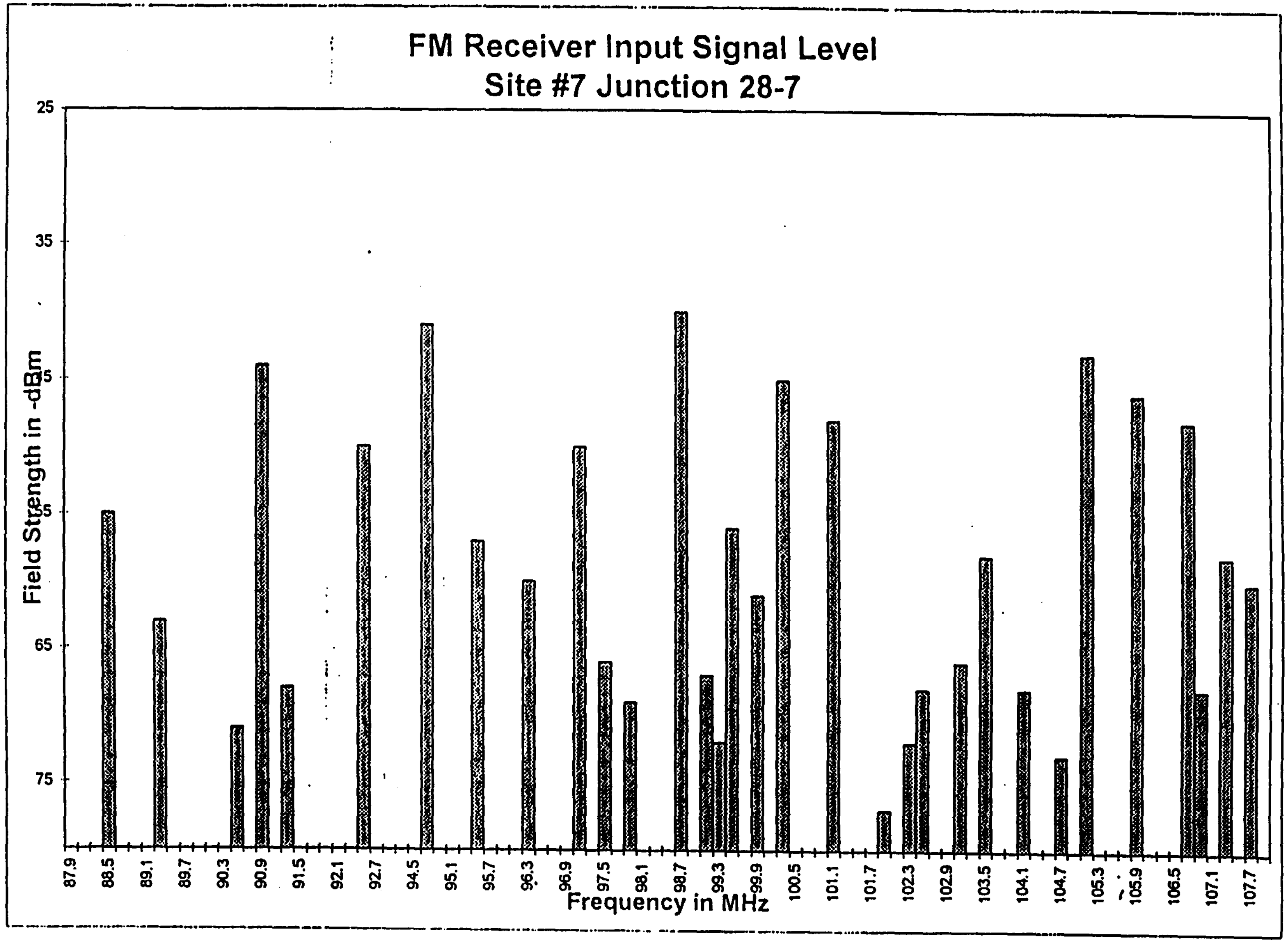
Similar analysis can be applied to all in-band DSB systems.

Conclusion

Based on the IBOC system characteristics measured in the laboratory tests, the protection ratios required for a DSB system has been established. With this information the number of stations receivable at each

FM Receiver Input Signal Level Site #7 Junction 28-7							
FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm
87.9	80	93.5	80	99.1	67	104.7	73
88.1	80	93.7	80	99.3	72	104.9	80
88.3	80	93.9	50	99.5	56	105.1	43
88.5	55	94.1	80	99.7	80	105.3	80
88.7	80	94.3	80	99.9	61	105.5	80
88.9	80	94.5	80	100.1	80	105.7	80
89.1	80	94.7	41	100.3	45	105.9	46
89.3	63	94.9	80	100.5	80	106.1	80
89.5	80	95.1	80	100.7	80	106.3	80
89.7	80	95.3	80	100.9	80	106.5	80
89.9	80	95.5	57	101.1	48	106.7	48
90.1	80	95.7	80	101.3	80	106.9	68
90.3	80	95.9	80	101.5	80	107.1	80
90.5	71	96.1	80	101.7	80	107.3	58
90.7	80	96.3	60	101.9	77	107.5	80
90.9	44	96.5	80	102.1	80	107.7	60
91.1	80	96.7	80	102.3	72	107.9	80
91.3	68	96.9	80	102.5	68		
91.5	80	97.1	50	102.7	80		
91.7	80	97.3	80	102.9	80		
91.9	80	97.5	66	103.1	66		
92.1	80	97.7	80	103.3	80		
92.3	80	97.9	69	103.5	58		
92.5	50	98.1	80	103.7	80		
92.7	80	98.3	80	103.9	80		
92.9	80	98.5	80	104.1	68		
93.1	72	98.7	40	104.3	80		
93.3	72	98.9	80	104.5	80		

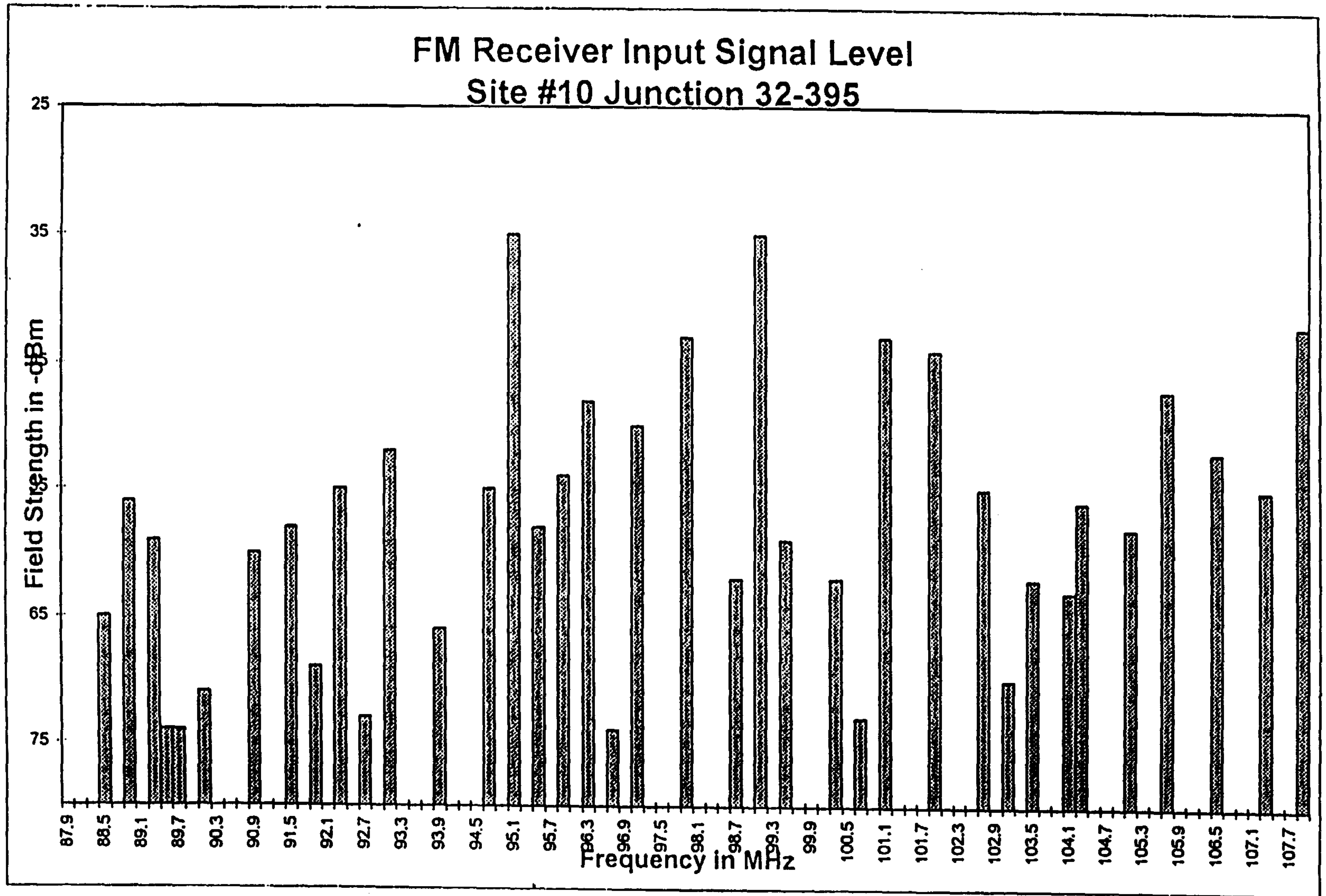
Table 1


FM Receiver Input Signal Level
Site #7 Junction 28-7
Field Strength in -dBm
25
35
45
55
65
75
87.9
88.5
89.1
89.7
90.3
90.9
91.5
92.1
92.7
94.5
95.1
95.7
96.3
96.9
97.5
98.1
98.7
99.3
99.9
100.5
101.1
101.7
102.3
102.9
103.5
104.1
104.7
105.3
105.9
106.5
107.1
107.7
Frequency in MHz

Graph 1

FM Receiver Input Signal Level Site #10 Junction 32-295							
FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm
87.9	80	93.5	80	99.1	35	104.7	80
88.1	80	93.7	80	99.3	80	104.9	80
88.3	80	93.9	66	99.5	59	105.1	58
88.5	65	94.1	80	99.7	80	105.3	80
88.7	80	94.3	80	99.9	80	105.5	80
88.9	56	94.5	80	100.1	80	105.7	47
89.1	80	94.7	55	100.3	62	105.9	80
89.3	59	94.9	80	100.5	80	106.1	80
89.5	74	95.1	35	100.7	73	106.3	80
89.7	74	95.3	80	100.9	80	106.5	52
89.9	80	95.5	58	101.1	43	106.7	80
90.1	71	95.7	80	101.3	80	106.9	80
90.3	80	95.9	54	101.5	80	107.1	80
90.5	80	96.1	80	101.7	80	107.3	55
90.7	80	96.3	48	101.9	44	107.5	80
90.9	60	96.5	80	102.1	80	107.7	80
91.1	80	96.7	74	102.3	80	107.9	42
91.3	80	96.9	80	102.5	80		
91.5	58	97.1	50	102.7	55		
91.7	80	97.3	80	102.9	80		
91.9	69	97.5	80	103.1	70		
92.1	80	97.7	80	103.3	80		
92.3	55	97.9	43	103.5	62		
92.5	80	98.1	80	103.7	80		
92.7	73	98.3	80	103.9	80		
92.9	80	98.5	80	104.1	63		
93.1	52	98.7	62	104.3	56		
93.3	80	98.9	80	104.5	80		

Table 2

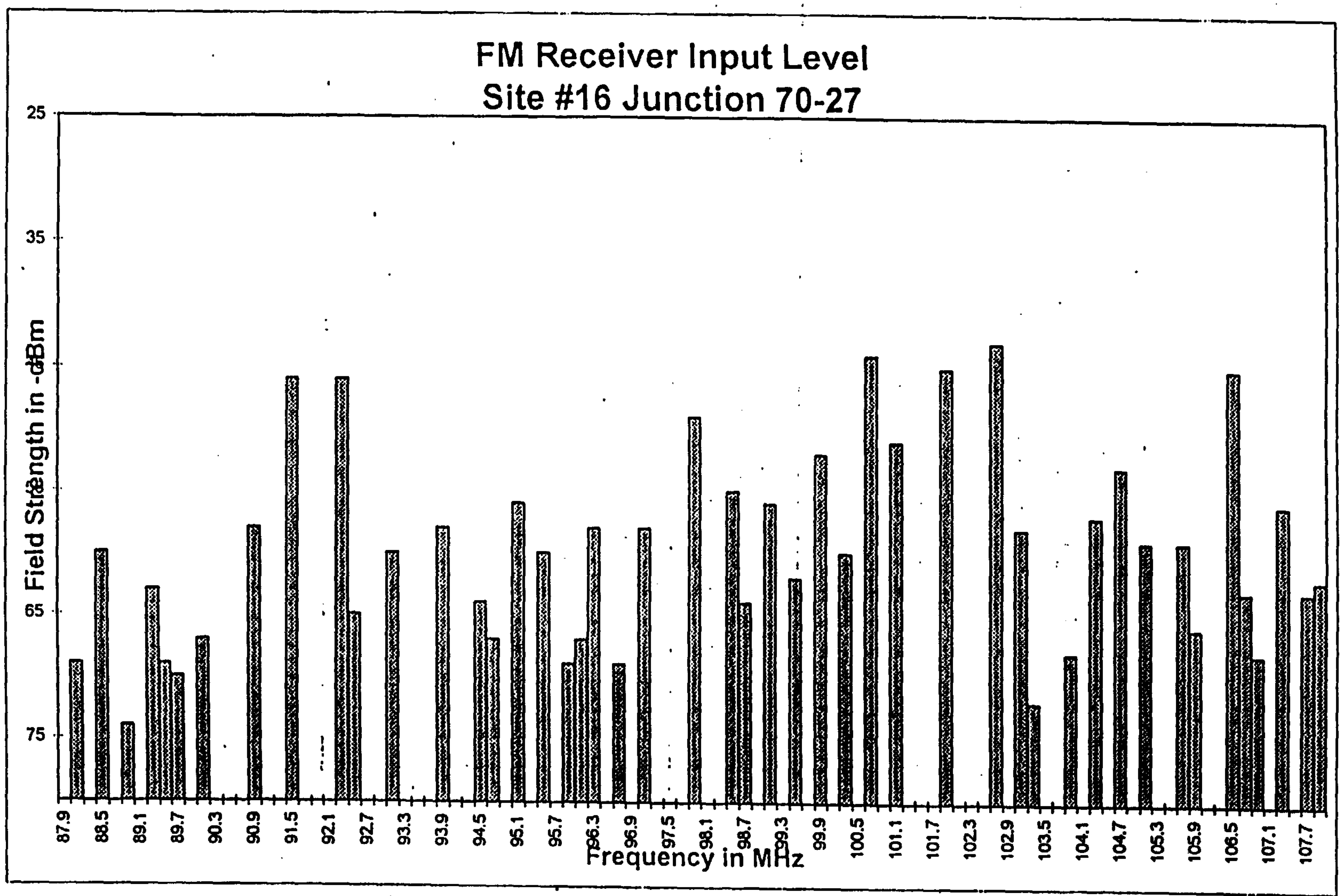


FM Receiver Input Signal Level
Site #10 Junction 32-395
Field Strength in -dBm
25
35
65
75
87.9
88.5
89.1
89.7
90.3
90.9
91.5
92.1
92.7
93.3
93.9
94.5
95.1
95.7
96.3
96.9
97.5
98.1
98.7
99.3
99.9
100.5
101.1
101.7
102.3
102.9
103.5
104.1
104.7
105.3
105.9
106.5
107.1
107.7
Frequency in MHz

Graph 2

FM Receiver Input Level Site #16 Junction 70-27							
FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm
87.9	80	93.5	80	99.1	56	104.7	53
88.1	69	93.7	80	99.3	80	104.9	80
88.3	80	93.9	58	99.5	62	105.1	59
88.5	60	94.1	80	99.7	80	105.3	80
88.7	80	94.3	80	99.9	52	105.5	80
88.9	74	94.5	64	100.1	80	105.7	59
89.1	80	94.7	67	100.3	60	105.9	66
89.3	63	94.9	80	100.5	80	106.1	80
89.5	69	95.1	56	100.7	44	106.3	80
89.7	70	95.3	80	100.9	80	106.5	45
89.9	80	95.5	60	101.1	51	106.7	63
90.1	67	95.7	80	101.3	80	106.9	68
90.3	80	95.9	69	101.5	80	107.1	80
90.5	80	96.1	67	101.7	80	107.3	56
90.7	80	96.3	58	101.9	45	107.5	80
90.9	58	96.5	80	102.1	80	107.7	63
91.1	80	96.7	69	102.3	80	107.9	62
91.3	80	96.9	80	102.5	80		
91.5	46	97.1	58	102.7	43		
91.7	80	97.3	80	102.9	80		
91.9	80	97.5	80	103.1	58		
92.1	80	97.7	80	103.3	72		
92.3	46	97.9	49	103.5	80		
92.5	65	98.1	80	103.7	80		
92.7	80	98.3	80	103.9	68		
92.9	80	98.5	55	104.1	80		
93.1	60	98.7	64	104.3	57		
93.3	80	98.9	80	104.5	80		

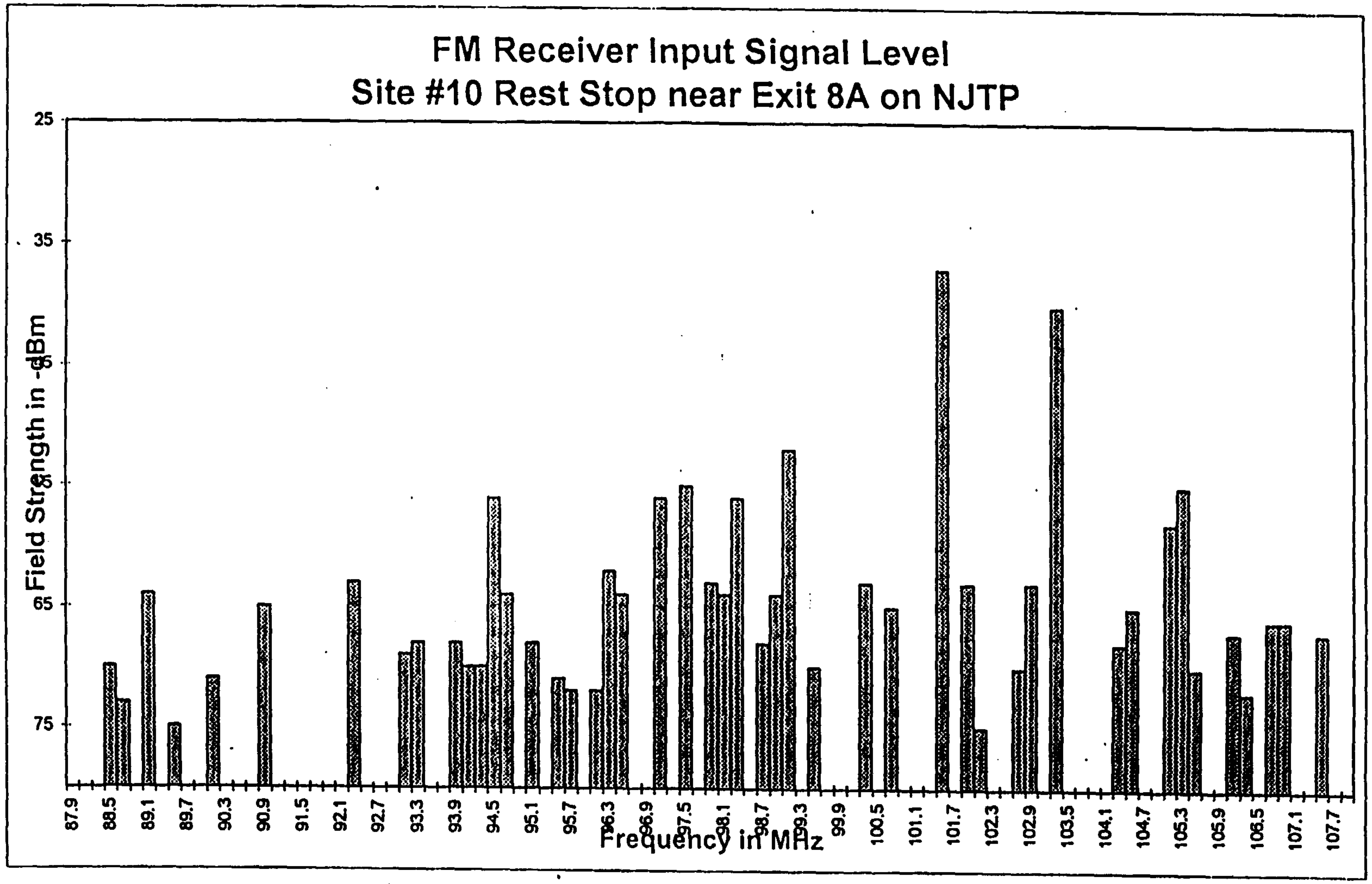
Table 3


FM Receiver Input Level
Site #16 Junction 70-27
Field Strength in -dBm
25
35
65
75
87.9
88.5
89.1
89.7
90.3
90.9
91.5
92.1
92.7
93.3
93.9
94.5
95.1
95.7
96.3
96.9
97.5
98.1
98.7
99.3
99.9
100.5
101.1
101.7
102.3
102.9
103.5
104.1
104.7
105.3
105.9
106.5
107.1
107.7
Frequency in MHz

Graph 3

FM Receiver Input Level Site #10 Rest Stop near Exit 8A on NJTP							
FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm	FM Band	Field Strength in -dBm
87.9	80	93.5	80	99.1	52	104.7	80
88.1	80	93.7	80	99.3	80	104.9	80
88.3	80	93.9	68	99.5	70	105.1	58
88.5	70	94.1	70	99.7	80	105.3	55
88.7	73	94.3	70	99.9	80	105.5	70
88.9	80	94.5	56	100.1	80	105.7	80
89.1	64	94.7	64	100.3	63	105.9	80
89.3	80	94.9	80	100.5	80	106.1	67
89.5	75	95.1	68	100.7	65	106.3	72
89.7	80	95.3	80	100.9	80	106.5	80
89.9	80	95.5	71	101.1	80	106.7	66
90.1	71	95.7	72	101.3	80	106.9	66
90.3	80	95.9	80	101.5	37	107.1	80
90.5	80	96.1	72	101.7	80	107.3	80
90.7	80	96.3	62	101.9	63	107.5	67
90.9	65	96.5	64	102.1	75	107.7	80
91.1	80	96.7	80	102.3	80	107.9	80
91.3	80	96.9	80	102.5	80		
91.5	80	97.1	56	102.7	70		
91.7	80	97.3	80	102.9	63		
91.9	80	97.5	55	103.1	80		
92.1	80	97.7	80	103.3	40		
92.3	63	97.9	63	103.5	80		
92.5	80	98.1	64	103.7	80		
92.7	80	98.3	56	103.9	80		
92.9	80	98.5	80	104.1	80		
93.1	69	98.7	68	104.3	68		
93.3	68	98.9	64	104.5	65		

Table 4


FM Receiver Input Signal Level
Site #10 Rest Stop near Exit 8A on NJTP
25
35
45
55
65
75
Field Strength in -dBm
87.9
88.5
89.1
89.7
90.3
90.9
91.5
92.1
92.7
93.3
93.9
94.5
95.1
95.7
96.3
96.9
97.5
98.1
98.7
99.3
99.9
100.5
101.1
101.7
102.3
102.9
103.5
104.1
104.7
105.3
105.9
106.5
107.1
107.7
Frequency in MHz

Graph 4